Experimental and numerical study of loading and wakes of tidal stream turbines in arrays

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• Background

• Experimental study of turbine arrays

• Wake of arrays by self-similar superposition

• RANS Blade Element CFD

• Summary
Loading of turbines in-array

Modelling of:
- Ambient turbulent flow,
- Velocity and turbulence of wakes (within and of array)
- Effect of array on onset flow
- Effect of array on waves and waves on loading

Afgan et al. 2013
Olczak et al. 2016

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Modelling of: ambient turbulent flow, velocity and turbulence of wakes (within and of array) effect of array on onset flow effect of array on waves and waves on loading
Tidal stream turbine modelling approaches

- Distributed Blade Force
- Blade Resolved
- Far-Wake
  - Semi-Empirical
    - inc. PARK, Thin Shear Layer
- Constant Actuator
- BEM Actuator
- Actuator Line
- Steady
- Un-steady

Afgan et al. 2013

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Array model evaluation

AIM: Assess accuracy of load and wake prediction of computationally efficient methods for array simulation

Net thrust and wake defines affect of array on coastal scale flow

Edmunds et al. Energies, 2015
Array model evaluation

AIM: Assess accuracy of load and wake prediction of computationally efficient methods for array simulation

Net thrust and wake defines affect of array on coastal scale flow

Experiment  
Prediction

Edmunds et al.  
Energies, 2015
• Experimental Study of Arrays
Array Experiments: Current & Wave flume
Array Experiments: Current & Wave flume

12 rotor array
Staggered: 3 | 4 | 5

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Rotor for testing at small geometric scale

Rotors designed to generate:
- **Equivalent momentum (CT),**
- **Representative swirl (TSR),**
- **Similar** angular momentum (CP).

Full-scale generic (thin)
1:70\(^{th}\) scale experiments at UoM

Whelan & Stallard EWTEC2011
Stallard et al. 2015
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Rotor for testing at small geometric scale

Rotors designed to generate:
- Equivalent momentum (CT),
- Representative swirl (TSR),
- Similar angular momentum (CP).

Diameter = 0.27 m

Full-scale generic (thin)
1:70\textsuperscript{th} scale experiments at UoM

Whelan & Stallard EWTEC2011
Stallard et al. 2015

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Single rotor wake in finite depth

For $X > 8D$, vertical profile recovered and **transverse profile self-similar**

$$U_{def}(X) = 0.864(X/D)^{-\frac{1}{2}} - 0.126$$

$$y_{1/2}(X) = 0.412R(X/D)^{\frac{1}{2}} + 0.5$$
Thrust and wake variation for arrays

e.g. 2 rows of 5 turbines

Onset velocity, rotor average from row 1 wake

Mean of all 1 min samples of thrust

(Standard deviation of thrust)
Superposition of single wake

\[ U_{\text{def}}(X) = 0.864(X/D)^{-\frac{1}{2}} - 0.126 \]
\[ y_{1/2}(X) = 0.412R(X/D)^{\frac{1}{2}} + 0.5 \]

\[ X = 2D \quad X = 4D \quad X = 8D \quad X = 10D \]

Experiments, \text{ -- Superposition}

Reasonable agreement. Rotor operating point assumed constant. Nearwake to model.
• RANS Blade Element
RANS blade element, method

$$dT = \rho \sigma \pi V^2 (C_l \cos(\phi) + C_D \sin(\phi)) r \, dr$$

$$dQ = \rho \sigma \pi V^2 (C_l \sin(\phi) + C_D \cos(\phi)) r^2 \, dr$$

Used in various studies, e.g.: Edmunds et al. Energies 2015; Turnock et al. Renewable Energy 2011...

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RANS blade element, performance

Flume

Stallard et al. 2015
J. Fluids Structures

Tow Tank

Bahaj et al. (2007)
Renewable Energy

Galloway et al. (2013)

Experiments, – RANS-BEM and - - - BEM

Momentum extraction (function of CT) well predicted, at low blockage
One row 5 turbines (partial fence)

Experiments:
> 450 $C_T$ samples

$C_T$ range per rotor:
3.2 to 5%

RANS-BEM with tip-speed-ratio as measured

For each rotor
RANS: +8 to 11%

- Experiments, - RANS-BEM and --- Superposition

Stallard et al. 2013
Olczak et al. 2016
Two rows 5 turbines aligned

RANS-BEM with tip-speed-ratio as measured

Experiments:
> 250 $C_T$ samples

$C_T$ range per rotor:
2.5 to 4.3%

RANS-BEM
Experiments
Two rows 5 turbines aligned

RANS-BEM with tip-speed-ratio as measured

For each rotor
Row 1: -5% to +8%
Row 2: -17% to +2%

Aggregate thrust
RANS: -2%

RANS-BEM Experiments
Two rows staggered

RANS-BEM with tip-speed-ratio as measured

RANS-BEM

Experiments

(c) Two rows staggered

Olczak et al. 2016
Stansby and Stallard 2016
Two rows staggered

RANS-BEM with tip-speed-ratio as measured

Single-wake superposition similar

(c) 2row34–Xsp 4D

RANS-BEM Experiments

Olczak et al. 2016
Stansby and Stallard 2016
Three rows staggered

RANS-BEM with tip-speed-ratio as measured

RANS-BEM Experiments

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Olczak et al. 2016
Three rows staggered

RANS-BEM with tip-speed-ratio as measured

For each rotor
Row 1: 1% to +4%
Row 2: +10% to 22%
Row 3: -10% to +38%

Aggregate thrust
RANS: +9%

RANS-BEM Experiments

Single-wake superposition similar mid-wake

Olczak et al. 2016
Stansby and Stallard 2016
Summary

• Array experiments at small-scale for representative channel blockage
  - 3-bladed rotors represent full-scale turbine thrust variation
  - **Measurement of loading, power and wake**
  - Arrays of 3 – 12 rotors, \( C_T \) to ±3% to ±5%

  - Near-wake model to relate to turbine operating point

• **RANS Blade Element CFD**
  - Validated for single rotor CT(TSR) and wake.
  - Thrust typically within 3-10% for single row.
  - Thrust accuracy varies with position in multi-row arrays.

To advance: onset turbulence and near-wake, support, waves …
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Further information (Open access)


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